

MANAGING DEMAND AND CAPACITY USING MULTI-SECTOR PLANNING AND FLEXIBLE AIRSPACE: HUMAN-IN-THE-LOOP EVALUATION OF NEXTGEN

Paul U. Lee*, Nancy M. Smith**, Thomas Prevot*, Jeffrey R. Homola*

*San Jose State University, **NASA Ames Research Center

Keywords: *NextGen, Multi-Sector Planner, Traffic Flow Management, Dynamic Airspace Configuration, Flexible Airspace Management*

Abstract

When demand for an airspace sector exceeds capacity, the balance can be re-established by reducing the demand, increasing the capacity, or both. The Multi-Sector Planner (MSP) concept has been proposed to better manage traffic demand by modifying trajectories across multiple sectors. A complementary approach to MSP, called Flexible Airspace Management (FAM), reconfigures the airspace such that capacity can be reallocated dynamically to balance the traffic demand across multiple sectors, resulting in fewer traffic management initiatives. The two concepts have been evaluated with a series of human-in-the-loop simulations at the Airspace Operations Laboratory to examine and refine the roles of the human operators in these concepts, as well as their tools and procedural requirements. So far MSP and FAM functions have been evaluated individually but the integration of the two functions is desirable since there are significant overlaps in their goals, geographic/temporal scope of the problem space, and the implementation timeframe. Ongoing research is planned to refine the humans' roles in the integrated concept.

1 Introduction

In the National Airspace System (NAS) of today, one of the primary goals and functions of air traffic management involves balancing the air traffic demand with current and predicted airspace capacity. When the demand exceeds the available capacity, flight delays and inefficiencies often occur as a result.

Airport capacity is often limited by hard constraints, such as physical runway space and reduced throughput due to local weather areas that make it impossible to use the airport and airspace resources during certain time periods. Aircraft expected to depart or land at these airports have to be queued and released when the resource becomes available again.

Managing airspace demand and capacity, on the other hand, has more degrees of freedom and options for reducing delays and inefficiencies. A variety of methods are available, such as traffic management initiatives (TMIs) that place aircraft in miles-in-trail or on playbook routes, rerouting aircraft outside of particular sectors, and/or implementing ground delay programs.

In overhauling the future air transportation system, increased capacity/throughput, better flight management, and improved flight and system efficiency are among the main drivers. The Next Generation Air Transportation System (NextGen) in the U.S. [1] and the Single European Sky ATM Research (SESAR) in Europe [2] are two programs that have been developed to transform the current system to the one envisioned for the future.

NextGen and SESAR aim to achieve increased capacity and improved efficiency through trajectory-based operations, greater use of tools/automation, and potentially reduced separation standards in high density airspace. Based on prior research on data communication (Data Comm), there is growing evidence that a properly introduced data communication infrastructure and additional decision support tools can increase the overall airspace capacity

by approximately 20% to 30% [3]. Further increases in productivity may require a substantial departure from current operations in which automation is responsible for central parts of the separation task instead of controllers.

While a radical paradigm shift may be the far-term vision of NextGen and SESAR, at least for the next one or two decades, there is a strong need for being able to balance the demand/capacity equation that dictates what can be accommodated by a single airspace sector. In this environment, controller workload and weather congestion remain two predominant factors that limit capacity and create delays in the high altitude airspace.

When demand for an airspace sector exceeds capacity, the balance can be re-established by reducing the demand, increasing the capacity, or both. The Multi-Sector Planner (MSP) concept has been proposed to better manage traffic demand and it has been examined both in the U.S. and Europe [4-7]. The MSP concept introduces an air navigation service provider (ANSP) position/function that modifies in-flight trajectories for aircraft within specific flows, reducing traffic or airspace complexity to manageable levels across multiple sectors. The potential benefit for such a position or function could be a more responsive and dynamic management of traffic with greater efficiencies relative to current management methods, thereby providing a better distribution of workload/resources at the sector level and reducing impact to system users.

An alternative to this approach, called Flexible Airspace Management (FAM), reconfigures the airspace such that capacity can be reallocated dynamically to balance the traffic across multiple sectors, resulting in fewer TMIs relative to current management methods. Flexible Airspace Management (FAM) is a component of a research project called Dynamic Airspace Configuration (DAC) which examines restructuring of airspace, flexible airspace reconfiguration, and generic airspace design [8].

MSP and FAM are complimentary ways of managing the demand-capacity imbalance. An integrated examination of these two concepts may provide greater benefit than examining the

two concepts in isolation. Sequential human-in-the-loop (HITL) simulations at NASA Ames' Airspace Operations Lab (AOL) have been conducted over the years to investigate MSP and FAM concepts individually. In this paper we will present both concepts, the HITL simulations that we have conducted, and the subsequent results. We will then describe future studies that can integrate both concepts.

2 Multi-Sector Planner

The MSP concept addresses demand/capacity imbalances by managing demand to reduce pressure on available resources. MSP functions looks ahead 30-90 minutes across multiple sectors, with a geographic and temporal scope that lies in between the more strategic focus of traffic management and the close tactical focus of the en route sector controller team. MSP operations support a number of different objectives or goals – e.g., managing sector controller workload; rerouting traffic around convective weather; time-based flow management (or other TMIs); and facilitating or supporting airspace reconfiguration.

The concept was originally developed as a set of functions that would be performed by a new facility position called the MSP. The multi-sector planning process includes problem identification, situation assessment, solution development, and plan coordination. Initial identification of the local area problem may occur in the TMU or control floor, while situation assessment and plan development may involve traffic management, one or more MSPs, and front line managers depending on the scope and complexity of the problem and its proposed solution. The person(s) who has developed the solution identifies the person(s) impacted by the plan and coordinates with them accordingly. The solution is then sent to the radar sector as a clearance request which the controller reviews and issues to the aircraft if it is acceptable.

2.1 Experimental Questions and Design

A HITL evaluation of the feasibility and possible benefits of the MSP concept for high altitude was completed in July 2009 [5]. This

study is a follow-up to a 2006 MSP study by Corker, et al. [4] to address several open issues. This earlier simulation compared the effectiveness of two MSP concepts in supporting multiple sector controllers, and focused on the MSP-radar controller interaction for one 3-sector test area. The 2006 study showed that an MSP working as a local area flow planner was able to effectively reduce controller workload. However, the simulation's scope was too limited to evaluate task management and coordination among MSPs, or to determine how the position would interact with traffic management and front line management.

The 2009 study added more positions and an expanded geographic area to investigate the concept's feasibility and benefits in a more complete operational environment. The toolset for MSP situation assessment, flow/trajecotry modification, and for coordination with others in plan development and execution was also greatly enhanced.

A particular focus of the 2009 simulation was to determine the need for creating a new staffed MSP position to perform these operations. To address this question, two test conditions with different ANSP team configurations were compared: a **baseline “No-MSP” condition** with traffic management coordinators (TMCs), front-line managers, and radar controllers, against the **MSP condition** where MSPs were added to this baseline team configuration.

2.2 General Experimental Set-up

MSP operations rely on an integrated set of automation tools to support situation assessment, solution development and plan coordination. The integrated set of multi-sector planning tools developed for the simulation is shown in Figure 1. The tools include:

- interactive load table and load graphs, traffic filters, and ‘what if’ solution assessment tools
- trial planning automation for single and multi-aircraft trajectory planning

- ground-ground and air-ground data communications for cross-party ANSP collaboration on problem evaluation, solution planning, and execution (not shown).



Fig. 1. MSP station prototype used during study in 2009

MSP tools were given to both MSPs and TMCs. They both modified trajectories for flow purposes but at different look-ahead horizons (30 – 60 min for the MSPs and 45+ min for the TMCs). Traffic scenarios consisted of convective weather and traffic load problems involving up to 1000 aircraft spanning several facilities in the central United States.

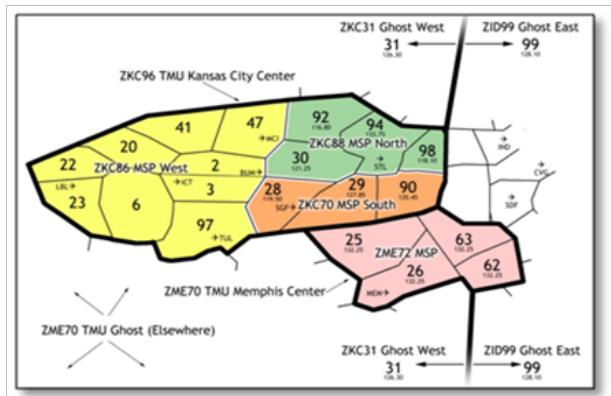


Fig. 2. MSP simulation airspace

The ‘test’ airspace included a ‘high fidelity’ area in the eastern half of the Kansas City Center (ZKC) that was staffed by most of the test participants: four air traffic controllers,

one area supervisor, one TMC, and two MSPs, along with three retired controller ‘confederates’ (see Figure 2, green and orange sectors). The airspace surrounding these ZKC East test sectors was staffed primarily by confederates who managed combined sectors and areas.

2.3 High Level Results

2.3.1 Aircraft Count and Controller Workload

Simulation results indicated that the planning operations were used effectively in both conditions and reduced sector demand to manageable levels. Test sector aircraft count showed a reduction from a 7-sector average that peaked around 22 aircraft when traffic was run ‘open loop’ (i.e., with no controller or planner intervention) to a 17 count peak in the MSP condition, and to a 18 count peak in the No-MSP condition (Figure 3a). Additionally, a plot of the average self-reported controller workload shows a modest reduction in controller workload in the MSP condition in line with this reduced sector count (Figure 3b).



Fig. 3. Aircraft count and workload averages for eastern ZKC test sectors.

Repeated measures ANOVA was performed on the averaged workload ratings between 30 to 75 minutes. Results showed a modest but significant reduction in workload in

the MSP condition compared to the No-MSP condition for both the Traffic Load and Weather scenarios ($M_{\text{No-MSP}} = 3.09$ vs. $M_{\text{MSP}} = 2.82$; $F(1,6) = 6.01$; $p < 0.05$). Although workload was not measured while recording the ‘open loop’ averages, it is a safe assumption that workload would have been unmanageable in the ‘open loop’ because the peak aircraft count would have exceeded 28 in the busiest test sectors without controller/planner intervention.

2.3.2 Conflicts and Weather Penetration

Weather penetration and number of conflicts data suggest an improved safety in the MSP condition (Figure 4). The top figure shows the number of aircraft that penetrated the weather cells across four different weather scenarios. The results show modest but significant reduction of weather penetrations in the MSP (red) compared to No-MSP condition (blue).

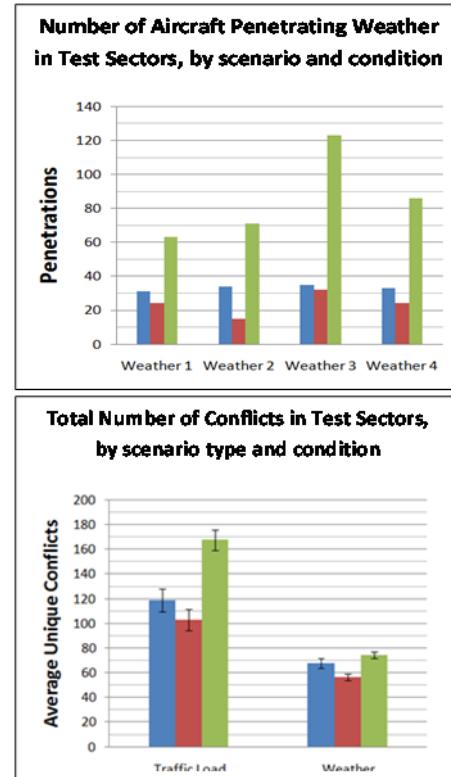


Fig. 4. Weather penetration counts and conflict event averages. Conditions: red=MSP, and blue=No-MSP. Green='open loop' measurements.

Similarly, the bottom figure also shows modest but significant reduction of aircraft conflicts in the MSP compared to No-MSP

condition in two different types of traffic congestions: Traffic Load and Weather.

Both MSP and No-MSP conditions showed large reductions of conflicts and weather penetrations compared to ‘open loop’ runs, suggesting that MSPs/TMCs were able to effectively resolve many of these problems in the test sectors. No significant effects in user efficiency measures – e.g., path length, flight time reductions or clearances per aircraft – were observed, but both MSP and No-MSP conditions provided satisfactory performance.

Although the improvements in the MSP condition are significant, it is perhaps *even more important* to note that the No-MSP condition was also effective. If MSP operations can be conducted without creating a new ANSP position, a seamless integration of promising MSP functions into the future NAS may be possible. Alternative team structures – e.g., one or more TMCs constructing weather avoidance routes with the MSP tools, with another STMC coordinating the planning activity – were suggested by participants in both teams, and might have been as effective. These results have led us to explore alternative team structures in our future MSP studies rather than separate MSP positions.

3 Flexible Airspace Management

The FAM concept addresses demand/capacity imbalances by reallocating the airspace capacity and the available controller resources to where the traffic demand is located. This is accomplished by reconfiguring airspace boundaries in a manner that is more flexible than is currently possible.

FAM operations allow the airspace configurations to be adjusted tactically to meet the changing traffic demand or airspace congestions due to weather or Special Use Airspace (SUA). Although FAM operations can be used reactively to solve traffic imbalances that have already occurred – similar to the way sectors are split today in response to traffic volume or weather – nominal FAM operations are envisioned to be pro-active during a 30 min to 2 hour look-ahead horizon across multiple sectors.

FAM planning phases include traffic demand / airspace capacity assessment up to 2 hours in advance, assessment of airspace configuration options, and plan coordination. Initial demand/capacity assessment may occur in the TMU or control floor depending on the scope of the problem. Assessment of airspace configuration options and plan development involves traffic management and front line managers (and MSPs if the position is fielded). Once the plan is in place, the new airspace configuration is coordinated between the front line managers and the controllers. Controllers preview the new airspace configuration, set up their equipment (e.g. open up new sector position if necessary), transfer aircraft ownership/radio frequency to the appropriate sectors, and brief the receiving controllers as appropriate.

Dynamic changes in the airspace configuration to meet changing traffic demand is a challenging task for human operators, in particular when changes take place across multiple sectors. Different airspace optimization algorithms are currently being researched and developed to find the optimal ways to reconfigure the airspace [9-12] and these algorithms can provide human operators with airspace configuration options to support the decision-making process.

3.1 Experimental Questions and Design

Prior research in airspace optimization algorithms showed potential benefits of FAM but its impact on the controllers was less known. Questions related to where, how often, and how fast airspace can be reconfigured needed to be examined to identify any adverse impact of flexible airspace transitions on the controllers, which could undermine the feasibility of the concept. A HITL simulation study was conducted in 2009 to better understand the controllers’ abilities to handle airspace transitions [13,14].

Traffic scenarios with varying types and severities of boundary changes (BCs) were used to test their impact on the controllers. The experiment consisted of four test conditions. A **Baseline** condition with no boundary changes

was used to establish the baseline workload and other performance metrics. Three additional conditions consisted of **Low**, **Medium**, and **High** severity of BCs. Figure 5 shows an example of airspace reconfiguration based on an algorithm with Medium BC severity.

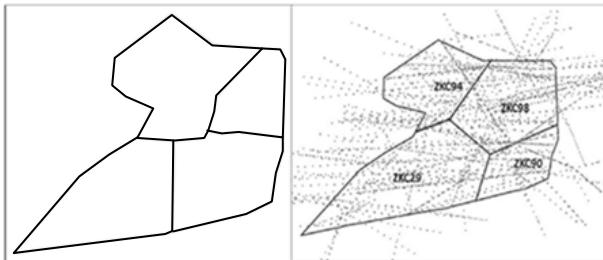


Fig. 5. Example airspace reconfiguration (right) based on the algorithm used for the Medium boundary change severity condition

For non-Baseline runs, there were a total of three sector boundary changes with BC frequencies ranging from 5 to 30 minute intervals within a one-hour traffic scenario. Three airspace reconfiguration algorithms [9-11] were selected based upon their approach and aggressiveness related to the severity of the sector boundary change and they were labeled as Low, Medium, and High according to the severity of the BCs established from subjective assessments of how the BCs would impact the controllers [13].

3.2 General Experimental Set-up

The test sectors were adapted from four high altitude sectors in ZKC (94, 98, 29 and 90) and were surrounded by the “ghost” sectors that handled the traffic that entered and exited the test sectors (see Figure 6).

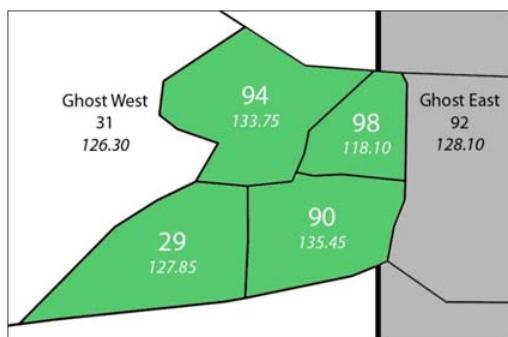


Fig. 6. FAM simulation airspace

The flows in the test scenarios consisted mostly of aircraft in level flight with the minimum altitude of FL 290. Traffic scenarios created traffic overload for sectors 94 and 90 while sectors 98 and 29 had capacity to absorb the excess demand.

The technology assumptions for the study were modeled after the assumptions in High Altitude Airspace (HAA) [15]. For the study, all aircraft were flying under Trajectory-Based Operations. They were assumed to be equipped with air-ground Data Comm with automated transfer-of-communication (Auto-TOC) as they were handed off between sectors. All positions had ground-ground and air-ground voice communication channels as they do today. The radar controllers (R-side) had conflict detection and resolution (CD&R) capabilities integrated into their displays.

3.4 High Level Results

Prior to the study, we hypothesized that the more drastic BCs would increase the number of tasks for the controllers, which in turn would result in greater controller workload. As expected, the greater BC severity increased the controller task loads, such as the number of handoffs and pointouts (see Figure 7). Furthermore, the results showed that the higher BC severity resulted in higher workload / lower acceptability ratings.

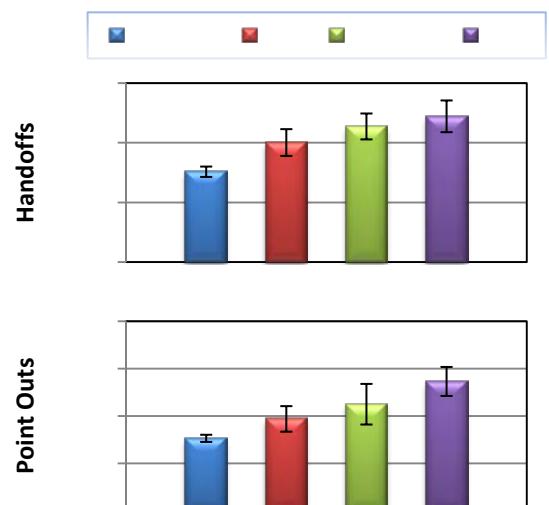


Fig. 7. Mean number of handoffs and pointouts for Low, Medium, and High BC severity as well as the Baseline

Per each boundary change, metrics such as airspace volume change, number of aircraft, and various task loads (e.g., handoffs, pointouts, etc.) were correlated with subjective metrics such as workload and acceptability. Hierarchical stepwise regression narrowed the explanatory variables for *overall workload during BCs* down to the following (listed in order of explanatory power): ***airspace volume change, aircraft count***, and number of ***late handoff acceptance***.

Since prior research showed that total aircraft count to be the main predictor of workload, it is notable that airspace volume change was a better predictor than the aircraft count during BCs. Using a similar analysis, ***aircraft gained/lost*** during the airspace transitions was the strongest predictor of the ***acceptability*** ratings.

Subjective feedback on workload and acceptability identified a similar set of predictors from the regression/correlation analyses. Interestingly, high frequency of BCs was not a factor for either workload or acceptability ratings in both objective and subjective metrics.

Participants commented that they would be able to handle large airspace volume changes if they had sufficient transition time to monitor the traffic and prepare for the BC, especially for Low and Medium BC severity conditions. A potential solution would be to reduce BC workload by creating a “gap” in the traffic such that fewer aircraft are present during airspace reconfiguration. Notably, an important caveat to the concept feasibility is that participants needed a reliable conflict probe to manage the BCs. They reported that they did not have adequate situation awareness of the incoming traffic for separation management without the help of the decision support tools.

4 Integration of MSP and FAM

As described in earlier sections, MSP and FAM are both envisioned to operate within a similar look-ahead horizon (i.e. less than 2 hours) across multiple sectors. Therefore, if both concepts are implemented in NextGen, a close integration of these two functions would be desirable. The results from the studies described

in this paper and current ongoing activities suggest that both MSP and FAM functions may be best integrated into the existing roles in the TMU and on the control floor.

In the TMU, one or more TMCs can manage traffic demand and capacity across multiple sectors by modifying aircraft trajectories and flows (i.e. MSP function) and/or selecting appropriate airspace configurations (i.e. FAM function). A person can be designated (e.g. Supervisor, TMC, or STMC) to utilize both the airspace and traffic flow plans and coordinate them with other TMUs, areas, or even facilities.

On the other hand, if the demand-capacity imbalance impacts only a few sectors or affects only one Area, the area supervisor of the impacted Area may be better suited to identify the problem and implement the solutions by re-routing a few aircraft or initiating a local airspace configuration change. The changes would be reported to the TMU to keep traffic management aware of local changes, similar to what is done today.

4.1 Moving Aircraft vs. Airspace

When MSP and FAM functions are integrated, ANSPs need to decide whether to re-route aircraft or reconfigure the airspace to solve the traffic congestion problem. Which options to exercise, as well as which option to exercise first will likely depend on a number of factors.

Certain traffic situations, such as deviations around weather cells, require moving the routes first; while others, such as reconfiguration due to traffic volume, may be resolved by airspace reconfiguration alone. In both cases, additional TMIs may be needed if the airspace reconfiguration cannot fully solve the traffic congestion.

Airspace reconfiguration has the potential to allow more aircraft to fly through a congested airspace, keeping more aircraft on their user-preferred routes. However, airspace reconfiguration also has the potential for higher coordination and workload cost to the ANSPs than re-routes and therefore should be used judiciously. Airspace reconfiguration seems to be ideal when there is a large change in the

average traffic volume over longer time durations (e.g. an hour or more).

The factors described above have been identified from past and ongoing research. Further studies are needed to identify and/or refine more factors that impact how to integrate TMIs with airspace reconfiguration.

4.2 Ongoing Research in MSP and FAM

In 2010, we have begun to explore the integration of the two concepts. First, a study in May explored allocating MSP function to the TMU and area supervisors in mixed equipage airspace. Only some aircraft were equipped with air-ground Data Comm to receive MSP initiated trajectory changes via data link while other aircraft received their trajectory changes via verbal route and altitude amendments from the radar controllers.

Secondly, a study in August 2010 plans to evaluate the role of the ANSP operator who assesses the airspace configurations and coordinates changes with the other team members. Leveraging prior studies, we will use a configuration that was used in the 2010 MSP study and add FAM functions. Results of these studies will be reported in 2011.

5 Conclusion

With added technology in NextGen, traffic demand-capacity can be managed by “fine-tuning” aircraft trajectories and airspace configurations flexibly to adapt to changes in the traffic situation. In the mid-term timeframe, two concepts, MSP and FAM, have been proposed to manage the demand and capacity side, respectively.

The two concepts have been evaluated with a series of HITL simulations at our laboratory to examine and refine the roles of the ANSPs, as well as their tools and procedural requirements. So far these concepts have been examined separately. As part of our ongoing research we integrate the two functions to continue to evaluate the effectiveness of both concepts and refine the roles of the ANSP operators. We hope that a combined approach will provide the future NAS with a greater ability to reduce the

impact of local traffic bottlenecks and therefore deliver aircraft to their destination more efficiently.

References

- [1] Joint Planning and Development Office. *Concept of Operations for the Next Generation Air Transportation System, version 2.0.*, 2007.
- [2] SESAR Consortium. *SESAR Master Plan D5*. MGT-0803-001-01-00., 2008.
- [3] Willems, B., and Hah, S. *A Future En Route Workstation Study (FEWS II): Part 1: Automation Integration Research* (DOT/FAA/TC-08/14,II). Atlantic City International Airport, NJ: Federal Aviation Administration William J. Hughes Technical Center., 2008.
- [4] Corker, K., Liang, D., Lee, P. and Prevot, T. *New Air Traffic Management Concepts Analysis Methodology: Application to a Multi-Sector Planner in US Airspace*, Proceedings of the 7th USA/Europe ATM Research and Development Seminar, Barcelona, Spain., 2007.
- [5] Smith, N., Lee, P. U., Prevot, T., Homola, J., Lee, H., Kessell, A., Brasil, C., Mainini, M. and Mercer, J. *A Human-in-the-Loop Investigation of Multi-Sector Planning Operations for the NextGen Mid-Term*, 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX., 2010.
- [6] Eurocontrol *En Route Multi-Sector Planning procedures*. (PHARE/EHQ/PAT-7.5.2.1;1.1). Brussels, Belgium, 1998.
- [7] Herr, S., Tiechmann, M., Poppe, M. and Suarez, N. *The Impact of Multi-Sector Planning and New Working Procedures on Controller Tasks*. In Proceedings of the 24th AIAA/IEEE Digital Avionics Systems Conference (DASC), Washington, DC., 2005.
- [8] Kopardekar, P., Bilmoria, K. and Sridhar, B. *Airspace Configuration Concepts for Next Generation Air Transportation*, Air Traffic Control Quarterly, Vol 16 [4]., 2008.
- [9] Brinton, C. and Pledgie, S. *Airspace Partitioning using Flight Clustering and Computational Geometry*. In Proceedings of the 27th Digital Avionics Systems Conference (DASC), St. Paul, MN., 2008.
- [10] Klein, A., Rogers, M. and Kaing, H. *Dynamic FPAs: A New Method for Dynamic Airspace Configuration*. Integrated Communications Navigation and Surveillance (ICNS) Conference. Bethesda, MD., 2008.
- [11] Yousefi, A., Khorrami, B., Hoffman, R. and Hackney, B. *Enhanced Dynamic Airspace Configuration Algorithms and Concepts*, Metron Aviation Inc., Technical Report No. 34N1207-001-R0., 2007.
- [12] Zelinsky, S. *A Comparison of Algorithm Generated Sectorizations*. Eighth USA/Europe Air Traffic

MANAGING DEMAND AND CAPACITY USING MULTI-SECTOR PLANNING AND FLEXIBLE AIRSPACE: HUMAN-IN-THE-LOOP EVALUATION OF NEXTGEN

Management Research and Development Seminar
(ATM 2009), Napa, CA., 2009.

- [13] Homola, J., Lee, P. U., Prevot, T., Lee, H., Kessell, A., Brasil, C. and Smith, N. *A Human-in-the-Loop Exploration of the Dynamic Airspace Configuration Concept*, AIAA Guidance, Navigation, and Control (GNC) Conference and Exhibit, Toronto, Canada., 2010.
- [14] Lee, P. U., Prevot, T., Homola, J., Lee, H., Kessell, A., Brasil, C. and Smith, N. *Impact of Airspace Reconfiguration on Controller Workload and Task Performance*, 3rd Int. Conference on Applied Human Factors and Ergonomics, Miami, FL., 2010.
- [15] FAA ATO Planning, Research and Technology. An Operational Concept for Mid-Term High Altitude (High Performance-Based) Airspace, draft version 4.17., 2010.

Contact Author Email Address

paul.u.lee@nasa.gov

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ICAS2010 proceedings or as individual off-prints from the proceedings.